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Utilizing angular displacement to monitor failure of coal seam floor

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Abstract

At present, it is difficult to accurately forecast the water inrush from coal seam floor. For safety, it is necessary to monitor and predict water inrush. Rock angular displacement can be observed easily and can show whether the coal seam floor has bent and destroyed or not. The elastic-plastic analysis and numerical simulation indicate that, 1) when angular displacement of rock is greater than the critical value, water inrush shall take place; 2) the critical value of angular displacement is $\frac{2(1+\mu)}{E}\tau_0$ by elastic-plastic analysis while the critical values of angular displacement in Buchun mine are 0.0019 radian for shale stone and 0.005 radian for fine sandstone, respectively, by numerical simulation. Based on these conclusions, we designed the early warning system of water inrush to obtain the laws of the damage depth of floor rock and angular displacement. The practice shows that using the method of rock angular displacement is very effective for monitoring and forecasting water inrush caused by coal seam floor failure.

Keywords: angular displacement; critical value; water inrush

1. Introduction

Water disaster is one of five disasters in mining. In North China, Ordovician Limestone water and thin limestone of coal seam floor is one main threaten to the mining safety. Many water inrush accidents prove that deformation and breakage of floor in working face (namely floor heave) is an important precursor of water inrush. Angular displacement of floor rock in the working face is one of main parameters for indicating deformation and breakage of floor rock. So studying the relatinship between angular displacement of floor rock and water inrush in working face is very significant for forecasting water inrush.

At present, there are many theories on mechanism of water inrush from the floor of working face, such as “Three Underlying Belts” Theory, “Intense seepage passage” Theory, “Plates and shells” Theory, “Key stratum” theory [1-5]. The researchers all consider that water burst from the floor of working face is related with the water pressure of the aquifer below the working face, mining pressure, the thickness and the capability of resisting failure of the relative aquifuge. To avoid water bursting from working face, it is necessary to prevent the aquifuge from being damaged. According to the stress distribution on working face floor, some researchers predicted possibility of water inrush from the working face floor [6-7]. However, due to complex conditions of the working face, it is very difficult to obtain the mechanical parameters of the working face floor accurately. Although some literatures studied the vertical displacement of rock [8-10], so far there are few articles to discuss the relationship between water inrush and angular displacement of rock. Only Dr. Wang Chong [11-12], put forward the fracture rotation gradient criteria. When rotation gradient value $|grad\ \theta|$ of one point in medium came to critical value $|grad\ \theta|_{cr}$, the point would fracture. But these conclusions were never applied for forecasting mine water disaster.

2. Theory analysis

2.1. The relationship between angular displacement and fragmentation of rock strata

In this paper, the angular displacement of rock in the working face floor means that the floor rock would bend and some angle would change in process of mining. As the surrounding of floor rock in the working face is fixed, the concept of angular displacement in this paper is consistent with the concept of shear strain in rock mechanics. According to the constitutive relationship of elasticity mechanics [13-14], the relationship between shear strain and shear stress can be described as formula (1).

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$$\gamma_{xy} = \frac{1}{G}\tau_{xy} \tag{1}$$

where γ_{xy} is shear strain, τ_{xy} is shear stress; G is stiffness modulus, which is determined by elastic modulus E and Poisson ratio μ , the relationship is as follow.

$$G = \frac{E}{2(1+\mu)} \tag{2}$$

According to plastic mechanics theory, when shear stress τ_{xy} comes up to shear strength τ_0 , the rock would fracture, and according to the formula (1), the shear strain is as follow.

$$\gamma_0 = \frac{1}{G}\tau_0 = \frac{2(1+\mu)}{E}\tau_0 \tag{3}$$

Because it is similar to the concept of shear strain, the critical value of angular displacement can be written as follow.

$$I = \frac{2(1+\mu)}{E}\tau_0 \tag{4}$$

When angular displacement (*i*) is more than or equal to the critical value (*I*), the rock would fracture. It can be written as follow.

$$i \geq I \tag{5}$$

So, according to the elastic-plastic mechanical, formula (5) is the rock strata breakage criterion based on the angular displacement.

After mining, because of pressure relief, the working face floor would bend upward and occur deformation [4,15], then produce angular displacement (namely floor heave). When the angular displacement of working face floor comes up to the critical value, the rock strata would fracture. When the angular displacement of key stratum comes up to its critical value, the depth of the fractured zone would expand quickly, even the whole aquifuge would fracture and water inrush would occur.

So monitoring the angular displacement change of working face floor, especially the key stratum, is helpful to monitoring the process of floor strata fractured and early warning to the water inrush from the working face.

2.2. Determine the critical value of the angular displacement

In formula (4), every parameter could be obtained by normal rock mechanics experiment. So according to formula (4) and some rock mechanics parameter, we calculated the critical value of angular displacement of some rocks. For example, using the rock mechanics parameter getting from the No.9113 working face in Bucun coal mine, we have calculated the corresponding critical values of angular displacement of the rock (Table 1).

Table 1. Critical values of rock angular displacement

Rock type	Modules of elasticity (GPa)	Poisson ratio	Shear strength (MPa)	Strength and Stiffness	Critical values of rock angular displacement(radian)
Fine sandstone	14.70	0.185	36.12	0.0062	0.00583
Areaceous shale	13.50	0.207	7.75	0.00559	0.00139
Clay shale	4.18	0.269	23.96	0.00165	0.01452
Limestone	11.34	0.245	9.87	0.00455	0.00216

3. Numerical simulation and analysis

In order to further analyze the relationship between the angular displacement of floor rock and fragmentation, we simulated the mining process of the No.9113 working face in Bucun coal mine by means of the ANSYS. The rock strata are from Xu Jiazhuang limestone to the top bedrock in this model. We replaced the Cenozoic impact with pressure, also exerted groundwater pressure and self-gravity. The model and boundary conditions were shown in Fig. 1.

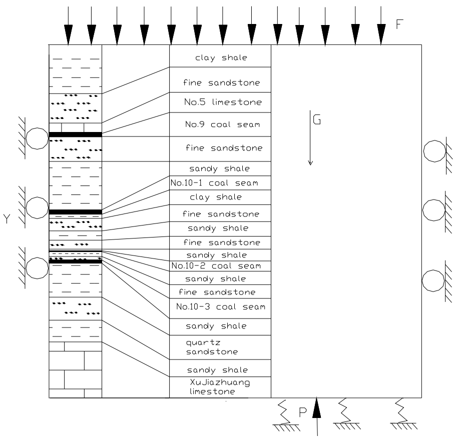

Fig. 1. Sketch of computation module and boundary conditions

The main lithologies in the working face floor include sandstone, siltstone, mudstone and coal seam. Their mechanical parameters were obtained by field test.

We simulated the stress distribution with different steps by the ANSYS. When working face advanced 38 meters, the compressive stress concentrated in the two ends of the work face. However, it was tensile stress because of pressure relief in the floor and roof of the goaf (Fig. 2). The compressive stress and tensile stress, shear stress concentrated obviously in the transition region (Fig. 3). Due to mining, the roof and floor in the goaf occurred not only elastic deformation (Fig. 4), but also plastic deformation in some region. The rocks were destroyed (Fig. 5).

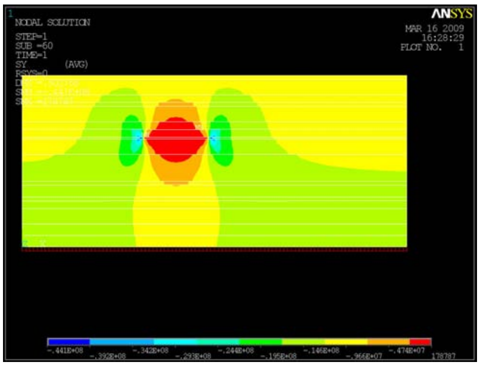

Fig. 2. The contours of Vertical stress in working face

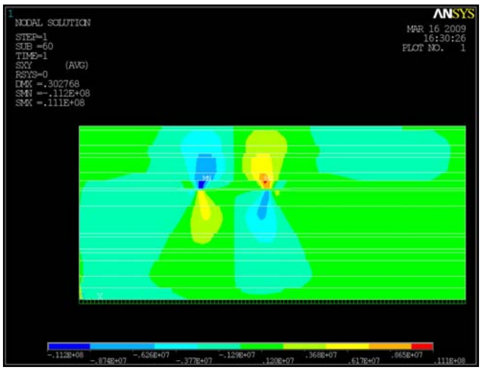

Fig. 3. The contours of shearing stress in working face

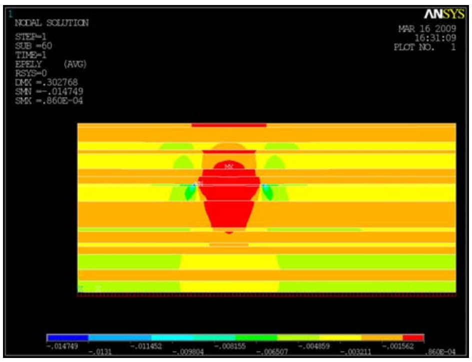

Fig. 4. The contours of elastic strain in working face

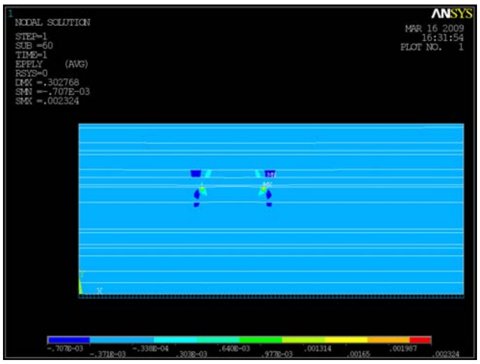

Fig. 5. The contours of plastic strain in working face

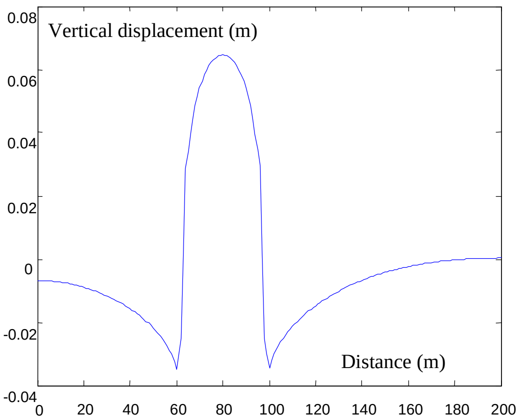

Fig. 6. The graph of Vertical displacement in working face floor

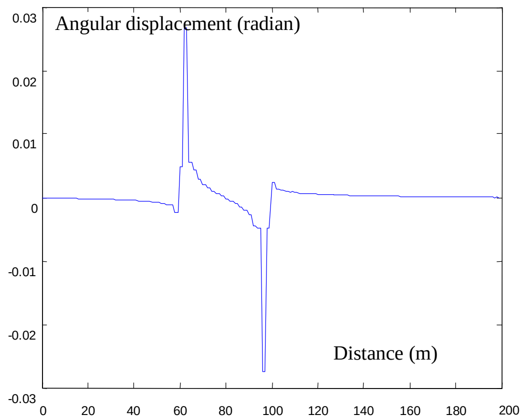

Fig. 7. The graph of angular displacement in working face floor

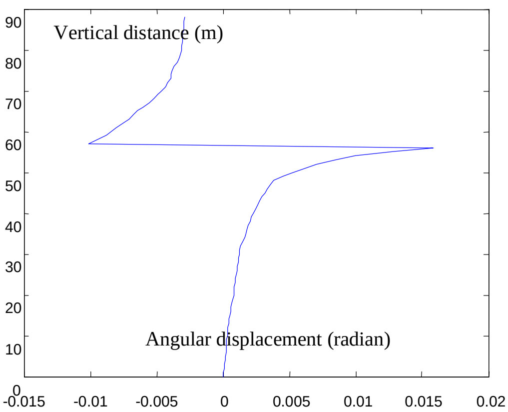

Fig. 8. The graph of angular displacement in working face floor

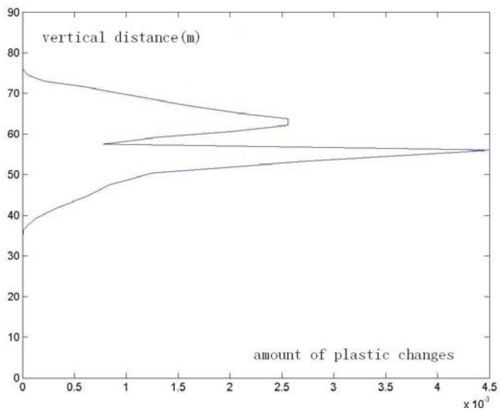

Fig. 9. The graph of plastic change in different depths of working face floor

The relationship between fragmentation and angular displacement were obtained by the ANSYS, and vertical displacement and angular displacement curves of different rock strata were obtained by the Matlab.

According to the curve, the vertical displacement in the immediate floor of working face was showed in Fig. 6. The vertical displacement value in the middle of the goaf was relatively large. However, the vertical displacement near the two sides of coal wall decreased rapidly, and the vertical displacement value under the coal wall was even negative. The results indicated that because the coal seam was mined, the floor rock was in the pressure relief and moved upward. But the rock under the coal pillar moved downward because of the action of support stress in advance.

Fig. 7 showed that the curves of angular displacement of the working face immediate floor. In this figure, the angular displacement value near the coal wall was relatively large, but it was small in the middle of the goaf.

Fig. 8 showed the curve of angular displacement in the vertical direction. The closer to the working face was, the larger angular displacement was. That was, the angular displacement in the immediate floor and immediate roof was obviously larger than others’.

Fig. 9 showed that the curve of plastic changes in the vertical direction. The closer to the working face, the larger was the amount of plastic changes. That was, the amount of plastic changes in the immediate floor and immediate roof was obviously larger than others’.

The following conclusions could be drawn by comparative analysis of the numerical simulation results:

- According to the Fig. 2, Fig. 4 and Fig. 6, the elasticity changes in the vertical direction of the working face floor, the vertical displacement and vertical stress in the floor are obviously relevant.
- According to comparative analysis of the Fig. 3, Fig. 5 and Fig. 7, the plastic damage in the working face floor, the shear stress and the angular displacement are obviously relevant. Where the angular displacement is larger, the rock strata are easier to fracture.
- According to comparative analysis of the Fig. 8 and Fig. 9, there is some quantitative relationship between the destruct and angular displacement in the working face floor. At 35 m from the working face in the floor and at 70 m in the roof, plastic deformation began to change (Fig. 9), and the angular displacements are 0.0019 and 0.005 radian respectively (Fig. 8). So the critical value of angular displacement of sandy shale and fine sandstone was 0.0019 and 0.005 radian respectively. The results are similar to value in Table 1.

4. Engineering example

In the No.9113 working face of the Bucun coal mine of Zibo Mine Group, the coal seam was threatened by water from limestone of Xujia Zhuang. To avoid water inrush, it conducted strip mining. In order to predict the possibility of water inrush, we observed the angular displacement changes of the No.9113 working face floor in the 9th mining belt. Six angular displacement sensors were laid in open-off cut and two angular displacement sensors were laid in upper ventilation passage. Also, two boreholes were drilled and ten angular displacement sensors were laid in different rock strata. These angular displacement sensors formed a geophysical multilayer space observing system, which can observe the dynamic angular displacement (Fig. 10).

At the same time, parallel electromagnetic exploration and microseismic monitor were laid in open-off cut and ventilation passage of the 9th mining belt, making up of a whole early warning system of water inrush, and collecting a lot of information.

The observation data from borehole 1# illustrated the change characteristic of angular displacement of the rock in the working face floor were as follows: borehole 1# was located in ventilation passage of the 9th mining belt, in which 5 angular displacement sensors were laid. The angular displacement sensors offered the data to draw the time varying curves of angular displacement (Fig. 11). From June 3 to June 5, face advanced distance was 5 m, and angular displacement from the borehole 1# was larger. In June 7, face advanced distance arrived at 7 m and reached borehole 1#. Advance stress disappeared and the angular displacement became small and the rock strata became flat. After June 9, when face advanced distance arrived at 13.5 m, borehole 1# was in the destressed zone and the angular displacement became large obviously.

According to angular displacement-depth curve of borehole 1# (Fig. 12), the angular displacement varied with depth of rock strata. The closer to the coal seam was, the larger angular displacement was. In other words, the closer to the coal seam was, the more easily the rock fractured.

The results of the theoretical calculation and numerical simulation showed that when the angular displacement was over 0.005 radian (0.29°) in the sandstone floor, the strata began to change plastically. The results of the field test showed that the angular displacement in the rock strata locating above 5 m was over 0.005 radian (0.29°), and the depth of the plastic failure belt was about 5 m.

The results of parallel electromagnetic exploration and microseismic monitoring methods showed that the depth of the damaged belt was about 5 m. It was very effective for predicting early the water inrush by the angular displacement observation method.

The working face was about 45 m away from the aquifer (limestone of Xujia Zhuang), so the damaged belt could not reach the aquifer and the mining was safe.

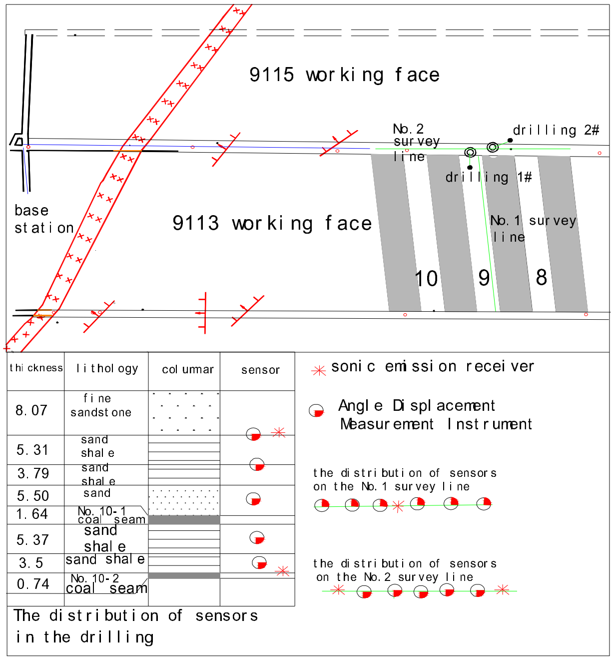

Fig. 10. The arrangement diagram of the seismic line and borehole

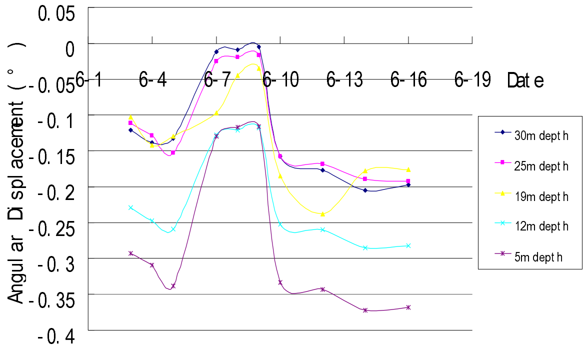

Fig. 11. Time curve of angular displacement in No.1 drilling

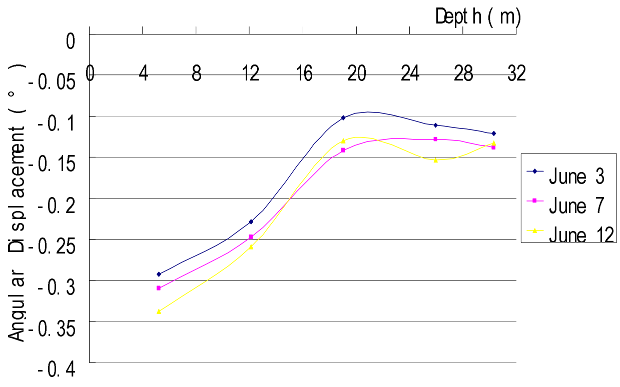

Fig. 12. The curve of angular displacement in different depth in No.1 borehole

5. Conclusions

According to theoretical and numerical simulation analysis, the following conclusions were drawn:

- The damage of the working face floor was mainly due to shear stress and obviously related to the angular displacement, but not related to the vertical displacement.
- When the angular displacement reach some critical value (according to the elasticity analysis
- $I = \frac{2(1+\mu)}{E}\tau_0$, in the Bucun coal mine it ranges from 0.0019 to 0.005 radian), the rock strata would fracture.
- According to the field measurement in the No.9113 work face, the angular displacement of the working face floor was related to the damage in working face floor and it was feasible to forecast water inrush by observing angular displacement of rock strata to monitor the floor strata destroyed.

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